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Multi-Objective Particle Swarm Optimization-Based Decision Support Model for Integrating Renewable Energy Systems in a Korean Campus Building

Minjeong Sim [1], Dongjun Suh [1,*] and Marc-Oliver Otto [2]

[1] Department of Convergence & Fusion System Engineering, Kyungpook National University, Sangju 37224, Korea; smj658@knu.ac.kr
[2] Department of Mathematics, Natural and Economic Sciences, Ulm University of Applied Sciences, Prittwitzstr, 10, 89075 Ulm, Germany; Marc-Oliver.Otto@thu.de
* Correspondence: dongjunsuh@knu.ac.kr; Tel.: +82-54-530-1482

Abstract: Renewable energy systems are an alternative to existing systems to achieve energy savings and carbon dioxide emission reduction. Subsequently, preventing the reckless installation of renewable energy systems and formulating appropriate energy policies, including sales strategies, is critical. Thus, this study aimed to achieve energy reduction through optimal selection of the capacity and lifetime of solar thermal (ST) and ground source heat pump (GSHP) systems that can reduce the thermal energy of buildings including the most widely used photovoltaic (PV) systems. Additionally, this study explored decision-making for optimal PV, ST, and GSHP installation considering economic and environmental factors such as energy sales strategy and electricity price according to energy policies. Therefore, an optimization model based on multi-objective particle swarm optimization was proposed to maximize lifecycle cost and energy savings based on the target energy savings according to PV capacity. Furthermore, the proposed model was verified through a case study on campus buildings in Korea: PV 60 kW and ST 32 m^2 GSHP10 kW with a lifetime of 50 years were found to be the optimal combination and capacity. The proposed model guarantees economic optimization, is scalable, and can be used as a decision-making model to install renewable energy systems in buildings worldwide.

Keywords: renewable energy systems; multi-objective particle swarm optimization; retrofit; lifecycle cost

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1. Introduction

The International Energy Agency (IEA) reports that carbon emissions from reckless fossil fuel use raise concerns with regard to energy security and the environment [1]. Specifically, the building sector has a long lifecycle and constitutes 40% of the total energy consumption [2]. In the building sector, campus buildings have regular schedules and high energy-saving potential because of the shorter operating periods during vacations. Thus, introducing renewable energy systems can have significant environmental benefits through energy efficiency improvement in the initial design and retrofitting of existing buildings [3]. Notably, renewable energy sources have been actively used in several applications including residential buildings [4], industries [5], university districts [6], logistics facilities [7], and seaports [8] for better energy management. Renewable energy systems used in buildings include photovoltaic (PV), solar thermal (ST), and ground source heat pump (GSHP) systems [9,10]. The PV system's output can be stably generated based on the panel surface or the direction of the roof [11]; thus, the PV installation capacity in Korea has increased by ~64.7% over the last decade [12]. In this manner, the renewable energy sector has exhibited significant growth, with solar energy at the center.

However, decision-makers must select appropriate measures in terms of energy performance, economy, and thermal comfort when performing a building retrofit for energy saving. Multicriteria models have been frequently used to evaluate building retrofit projects, and various multi-objective optimization studies have recently been conducted to increase the energy efficiency of buildings. Kumbaroglu and Madlener [13] proposed a technical and economical optimal retrofit for the building envelope and heating system for office buildings in Germany via simulation analysis. Hong et al. [14] developed an optimization model that simultaneously considered thermal comfort, heating energy consumption, and environmental and economic value using a multi-objective genetic algorithm (GA) to build a library and proposed seasonal results. Fesanghary et al. [15] proposed the optimal envelope of the building using a harmonization algorithm to minimize the lifecycle cost (LCC) of the building and the emission of carbon dioxide equivalents for residential buildings. Diakaki et al. [16] proposed an alternative building envelope and heating/cooling systems, minimizing the annual primary energy consumption, carbon dioxide emissions, and initial investment cost in a 1000 m^2 residential building. Elbaset et al. [17] proposed a multi-objective particle swarm optimization (MOPSO) model that maximizes the renewable energy fraction while considering the power supply probability and energy cost for a grid-connected hybrid PV/wind turbine-based system. Asadi et al. [18] confirmed the feasibility of the proposed approach through case studies by optimizing the renovation costs, energy saving, and thermal comfort of residential buildings. Wright et al. [19] proposed a design process that maximizes the user's thermal comfort and minimizes cost using a multi-objective GA. Malatiji et al. [20] formulated a multi-objective optimization model that maximizes energy saving and minimizes the payback period using a GA. Marcado et al. [21] proposed the use of intelligent technology to optimize the size of a hybrid renewable energy system using solar and wind power. Furthermore, Gonzalez et al. [22] optimized the size of a hybrid grid-connected solar-wind system to minimize cost (Table 1).

The multi-objective optimization criteria in recent studies mainly focused on thermal comfort, initial investment costs, and energy efficiency.

Retrofitting a building requires the initial investment costs as well as maintenance and replacement costs to be considered; therefore, it must be analyzed in terms of the building's lifecycle. LCC analysis can be performed for cost-effectiveness by estimating the total cost incurred at each stage, from the design stage to the disposal stage of the project. Cost-effectiveness can be calculated using methods such as economic viability, net present value (NPV), internal rate of return, the overall rate of return, and benefit-cost ratio. The project cost during the LCC period cannot be directly compared because of the time value of money. NPV is a method for comparing project costs by converting them to a value equal to the base date of the project cost and is the most widely used when evaluating cost optimization [23].

This study proposed a multi-objective optimization model that uses LCC analysis to help make the decisions necessary for the building design stage and retrofit plans for campus buildings through case studies. The optimization model involves determining the building's capacity and area, proposing suitable renewable energy systems for various alternatives available to decision-makers.

Renewable energy systems primarily used in the building sector of Korea are PV, ST, and GSHP. Several studies have developed a design model that considers economic and environmental factors. Koo et al. [24] developed an economically and environmentally optimal model for a residential building in Korea using various energy saving techniques and PV. Bae et al. [25] analyzed self-energy sufficiency and payback periods in Korea and Canada using PV-ST and GSHP, and they proposed an economical solution. Suh et al. [26] confirmed that the combination of PV and GSHP systems improves energy performance to achieve zero energy in community buildings in Korea. In addition, according to the Korea Energy Agency's new and renewable energy supply statistics [27], the annual renewable energy production in 2018 was 1,977,100 TOE for PV, 205,500 TOE for GSHP, and 27,400 TOE for ST, and the energy production using PV was the largest, followed by GSHP and ST in that order. Thus, herein, PV, ST, and GSHP were selected for energy performance and economic feasibility analysis of renewable energy systems.

Table 1. Summary of previous studies.

Author	Algorithm	Objective
Hong et al. [14]	NSGA-II algorithm	Minimum predicted mean vote for the building occupants' indoor environmental quality acceptance level. Minimum initial investment cost. Minimum thermal energy consumption. Minimum net present value for the lifecycle economic value. Minimum global warming potential for the lifecycle environmental value.
Feasanghary et al. [15]	Harmony search algorithm	Minimum LCC. Minimum carbon dioxide equivalent emissions.
Diakaki et al. [16]	Compromise programming	Maximum energy consumption. Minimum CO2 emissions. Minimum initial investment cost.
Barakat et al. [17]	Particle swarm optimization algorithm	Minimum loss of power supply probability. Minimum cost of energy. Maximum renewable energy fraction.
Asadi et al. [18]	Tchebycheff optimization	Minimum retrofit cost. Minimum energy saving. Minimum thermal comfort.
Wright et al. [19]	Genetic algorithm	Minimum HVAC system energy cost. Maximum occupant thermal comfort.
Malatji et al. [20]	Genetic algorithm	Maximum energy saving. Minimum payback period.
Mercado et al. [21]	Genetic algorithm	Minimum reliability value. Maximum initial cost.
González et al. [22]	Genetic algorithm	Minimum net present value.

Furthermore, PV is the fastest growing system among renewable energy systems because of technological advancements and falling financial costs [28]. However, the PV system finds it challenging to stably respond to the building load because of intermittent energy generation and the limit of the installed PV system's installation capacity based on the building's roof area. Therefore, we applied ST and GSHP together with the renewable system of both the heating load and the hot water supply. This model maximized the LCC of the entire project, including energy savings and energy generation sales. Therefore, energy savings were achieved by dividing into 10–20%, 20–30%, and 30%—sections of the expected energy consumption based on the PV system's capacity.

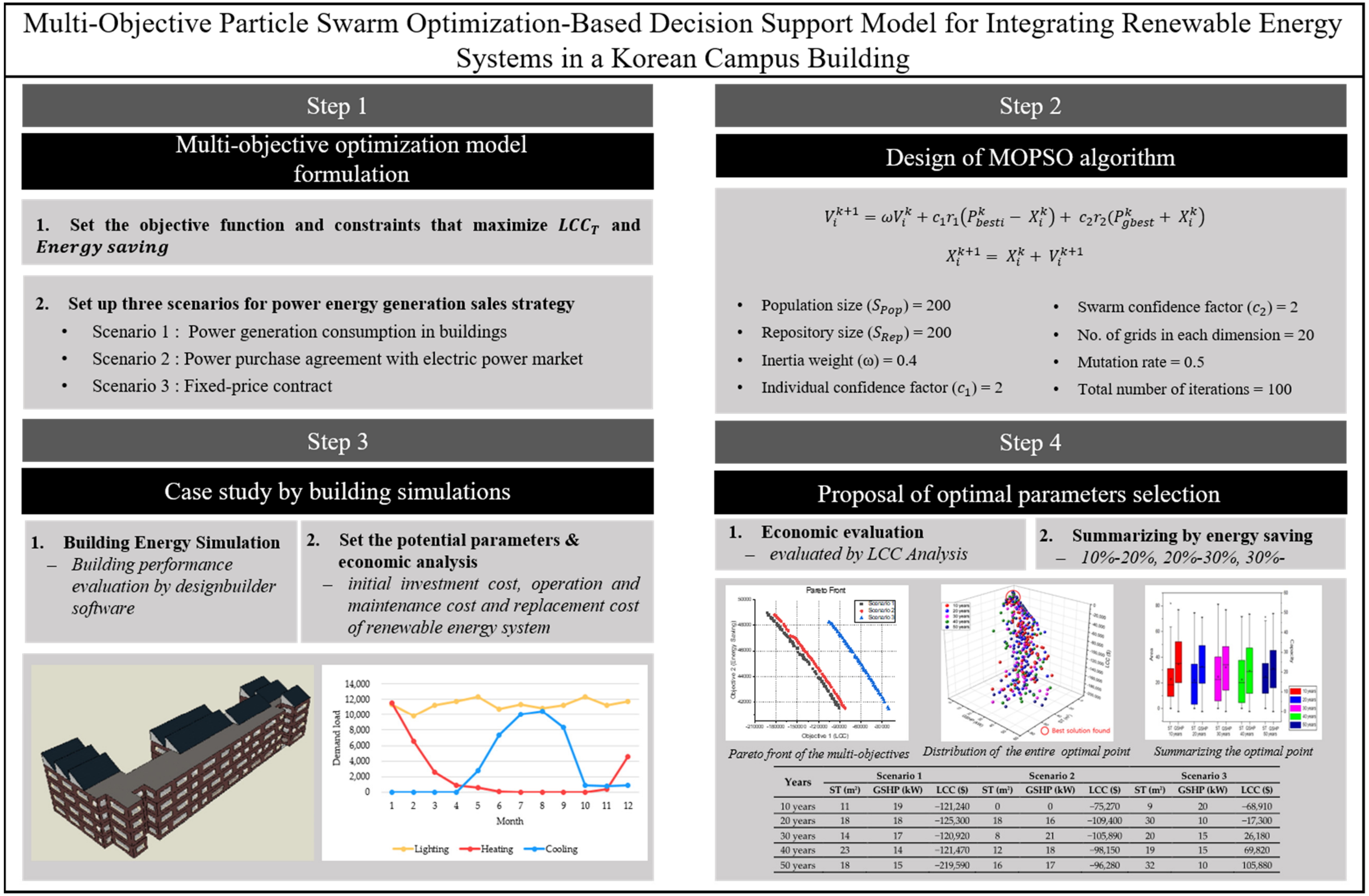
Herein, a case study was performed by analyzing the application of renewable energy systems to campus buildings in Korea. In addition, through the expansion and application of the analysis results, the proposed system can be used as a decision-making model for the installation of renewable energy systems in buildings in other countries and regions.

The proposed model combines renewable energy systems; however, the number of design variable combinations is large, and it is impossible to confirm all combinations because the nonlinear objective function is included. However, this complex problem can be solved by deriving several optimal solutions using the particle swarm optimization (PSO) algorithm, a meta-heuristic optimization algorithm. Kennedy and Eberhart initiated PSO in 1995, and it is an iterative optimization algorithm that simulates social behavior [29]. PSO is similar to the GA in that it mimics a cluster entity, and similar convergence results can be obtained. However, it has a faster execution speed than the GA and is widely used because the convergence time is shortened, particularly when processing complex design variables [30]. Moreover, Lee et al. [31] compared the performance of PSO and differential evolutional algorithms, and PSO proposed a better solution. Therefore, the PSO algorithm was adopted to solve the optimization problem, and a case study was conducted to verify the proposed model.

Many studies have been conducted to optimize energy efficiency in buildings [14–22]. However, multi-objective optimization was performed only for passive and HVAC systems in those studies, and renewable energy systems were not considered. Further, studies on the installation of renewable energy systems did not consider energy policies with sales strategies. The laws and policies related to renewable energy are being established as the importance of renewable energy resources is increasing worldwide. Moreover, several energy sales strategies suitable for the situation have emerged in various regions and countries. Including energy transaction, generation, storage, distribution, and consumption in these strategies is essential to guarantee the reliability of electricity and minimize the cost by designing the indiscriminately installed renewable energy systems according to the optimal lifetime and combination of each system. The analysis results aim to guarantee economic optimization and can be used as a decision-making model in other countries and regions with similar energy policies to this study.

Herein, we analyzed optimization problems based on three different scenarios including the sizing and the lifetime variation of both ST and GSHP systems with respect to a fixed capacity variable of the PV system, the most widely distributed and economically efficient PV system in Korea. Summarily, the problem statement for this study is as follows. The objective was to maximize energy-saving and the sum of the investment cost, the operation and maintenance cost, the replacement cost, and the monetary benefits of power generation. The constraint cannot exceed the maximum capacity and area of the systems, the target energy savings, the variable of an optimization problem in the ST area, and the capacity of GSHP systems. The three analysis scenarios were as follows. The first scenario incorporated using power generation directly into the building, and the second scenario established a power purchase agreement (PPA) with the electric power market. Finally, the third scenario entered a fixed-price contract directly. An appropriate strategy can be selected based on the scenario and objective energy savings. To confirm the trade-off for the objective function, the results are shown using the Pareto-front, and detailed variables can be confirmed with a scatter plot.

The rest of the article comprises four sections, and Figure 1 shows the research framework. Section 2 introduces the research methodology, while Section 3 presents the simulation analysis of the case study. Section 4 describes the experimental results and discussion. Section 5 presents the conclusions of this study.



Years	Scenario 1			Scenario 2			Scenario 3		
	ST (m²)	GSHP (kW)	LCC ($)	ST (m²)	GSHP (kW)	LCC ($)	ST (m²)	GSHP (kW)	LCC ($)
10 years	11	19	−121,240	0	0	−75,270	9	20	−68,910
20 years	18	18	−125,300	18	16	−109,400	30	10	−17,300
30 years	14	17	−120,920	8	21	−105,890	20	15	26,180
40 years	23	14	−121,470	12	18	−98,150	19	15	69,820
50 years	18	15	−219,590	16	17	−96,280	32	10	105,880

Figure 1. Research framework.

2. Research Methodology

This study used two maximized objective functions. The first function was the maximization of total LCC, which is the sum of all costs incurred from the design stage to the lifecycle, and the decision maker can compare and analyze each alternative. In this study, the initial investment cost, the operation and maintenance cost, the replacement cost and the monetary benefits obtained from power generation were included. To maximize LCC, the monetary benefit was expressed as a positive number, and the remaining costs were all expressed as negative numbers. The second function was the maximization of energy-saving designed by adding the amount of power generated by each renewable energy system. The two objective functions were expressed as Equations (1) and (2).

$$Obj_1 = Max\ (LCC_T) \tag{1}$$

Further,

$$Obj_2 = Max\ (Energy\ saving), \tag{2}$$

where the LCC_T of the project can be calculated using Equation (3).

$$LCC_T = LCC_{PV} + LCC_{GSHP} + LCC_{ST} + Profit, \tag{3}$$

Here, LCC_T is the sum of the total amount used for the entire project period, which is the sum of the PV, GSHP, and ST NPVs as well as the monetary benefit from the energy generation of renewable energy systems. The renewable energy system's LCC is calculated using Equations (4)–(6):

$$LCC_{PV,ST} = IC + \frac{(1+i)^n - 1}{i(1+i)^n} O\&M + \sum \frac{1}{(1+i)^n} R, \tag{4}$$

where IC is the initial investment cost, i is the real discount rate, $O\&M$ denotes the operation and maintenance cost, and R is the replacement cost.

$$LCC_{GSHP} = IC + \frac{(1+i)^n - 1}{i(1+i)^n} O\&M \tag{5}$$

The real discount rate i can be calculated using Equation (6) [32].

$$i = \frac{(1+i_n)}{(1+f)} - 1, \tag{6}$$

Here, i_n is the nominal discount rate, and f is the inflation rate.

$Profit$ from renewable energy generation is calculated using Equation (7).

$$Profit = S_n \times Energy\ saving \times \frac{(1+i)^n - 1}{i(1+i)^n},\ n\ \in \{Scenario\ 1 \sim 3\}, \tag{7}$$

where S_n is the energy unit price for each scenario. $Energy\ saving$ is the amount of energy saved by generating renewable energy systems, calculated using Equation (8) by adding the generation amount of each renewable energy system.

$$Energy\ saving = G_{PV} + G_{GSHP} + G_{ST}, \tag{8}$$

Here, G_{PV} is the power generation of PV, G_{GSHP} is the power generation of GSHP, and G_{ST} is the power generation of ST.

The constraints of the objective function are shown in Equations (9) and (10):

$$C_x^{min}\ \leq\ C_x \leq C_x^{max},\ x \in \{PV,\ GSHP,\ ST\}, \tag{9}$$

where C_x is the capacity and area of element x and cannot exceed the maximum capacity and area of each system. Furthermore, each scenario satisfies the constraints shown in Equation (10).

$$Energy\ saving\ \leq OE, \tag{10}$$

where OE is the objective energy saving.

2.1. Power Generation Sales Strategy

The power generated by the renewable energy system can be used in many ways. It can be divided into a strategy to directly reduce the energy use of a building and a strategy that makes a profit by selling the amount of electricity generated. An LCC analysis will be conducted by dividing energy sales methods used to expand renewable energy generation in countries, such as Korea, the USA, Belgium, and Australia, into scenarios. Scenarios are classified into three categories, and the first scenario is a method used directly for buildings, wherein electricity costs are applied. The second scenario is to enter into a PPA with the electric power market and apply the monthly weighted average system marginal price, which is $0.081. In the third scenario, $0.14 was set to the renewable energy supply obligation as a method for selling through a fixed-price contract. The scenarios used are listed below.

- Scenario 1: Power generation consumption in buildings.
- Scenario 2: PPA with electric power market.
- Scenario 3: Fixed-price contract.

2.2. MOPSO Algorithm

MOPSO was used to solve the retrofit problem of buildings. MOPSO is a global optimization technique that achieves objective function optimization by allowing individual particles to have the properties of position and velocity and by allowing the particles to be simultaneously improved through iterative calculations. Therefore, the speed of the particles and the size of the search space determine the accuracy of the search. Large population sizes and iterations require additional computation and increase both computation time and the algorithm's reliability.

In addition, PSO has similar performance to GA. Furthermore, it is easy to develop and has excellent computational efficiency [33]. MOPSO is a multipopulation-based algorithm, and it is not easy to fall into the local optimal solution. Therein, each particle moves toward P_{best} and P_{gbest}, which have good objective function values, but if the minimum error criterion is not reached, the algorithm is repeated. Kennedy [33] stated that the algorithm becomes stuck in the local optimal solution if it iterates more than 3000 times without reaching the criterion. Several studies have been conducted to find the optimal solution using the PSO algorithm, and Fadaee and Radzi [34] proposed PSO as a method to obtain a global optimal solution in the design of a hybrid renewable energy system.

The MOPSO procedure implemented herein was adopted from [35]. In addition, the algorithm was implemented and executed in MATLAB (R2019b); The pseudo-code (Table 2) of the MOPSO is shown as follows.

Table 2. The pseudo-code of MOPSO.

01	Set MOPSO parameters. Population size (S_{Pop}) = 200, repository size (S_{Rep}) = 200, inertia weight (ω) = 0.4, individual confidence factor (c_1) = 2, swarm confidence factor (c_2) = 2, number of grids in each dimension = 20, mutation rate = 0.5, total number of iterations = 100.
02	Set the lower and upper boundaries of the search variables, respectively. • Lower and upper boundaries of the capacity of GSHP systems [0, 150]. • Lower and upper boundaries of the area of ST systems [0, 170].
03	**For** $i = 1:\ S_{Pop}$
04	Randomly initialize the population of particles having positions X_i. $X_i = \{C_{GSHP}, C_{ST}\}$
05	Velocities V_i are set to zero. $V_i = 0$
06	Calculate the fitness of particles and find the index of the best particle. $P_{besti} = X_i$
07	**End**
08	Store the positions of the particles representing nondominated vectors in the repository *Rep*.
09	k = 0
10	**While** $k \leq MAX_{iter}$
11	**For** $i = 1:\ S_{pop}$
12	Select the particle with the best fitness value as P_{gbest}. $P_{gbest} = selectP_{gbest}\ (Rep)$
13	Update the velocity of the particles. $V_i^{k+1} = \omega V_i^k + c_1 r_1 \left(P_{besti}^k - X_i^k\right) + c_2 r_2 \left(P_{gbest}^k + X_i^k\right),$ where r_1, r_2 is an acceleration constant, and a value between 0 and 1 is randomly determined.
14	Update the position of the particles. $X_i^{k+1} = X_i^k + V_i^{k+1}$
15	The value of the objective function is calculated using the position of each particle, and the repository is updated by comparing it with the values of the object stored in the repository.
16	If the fitness of X_i is excellent by comparing the past P_{besti} with the present X_i, the particle's position is updated using: $P_{besti} = X_i$
17	**End for** Add the nondominated particles to the repository. Remove dominated members of the repository.
18	**End while**

3. Case Study

To verify the applicability of the proposed optimization model, a campus building in Korea was used as a case study. Campus buildings are representative energy-intensive buildings, constituting more than 40% of the energy consumption of the building sector [36]. However, the campus building comprises research and class facilities, the operating period is constant, and the energy-saving potential is high because of the reduced operating period during vacation periods compared to the occupancy period. Therefore, the effect of applying renewable energy systems varies according to the energy pattern representing the building's schedule and characteristics. In this study, an office building comprising four floors and panning an area of 4169 m^2 was selected as the target building. The glass area of the building was 611 m^2, and the floor height was 3 m. Figure 2 shows a three-dimensional model produced using a DesignBuilder (V6.1.3) [37] simulation of the building analyzed in the case study.

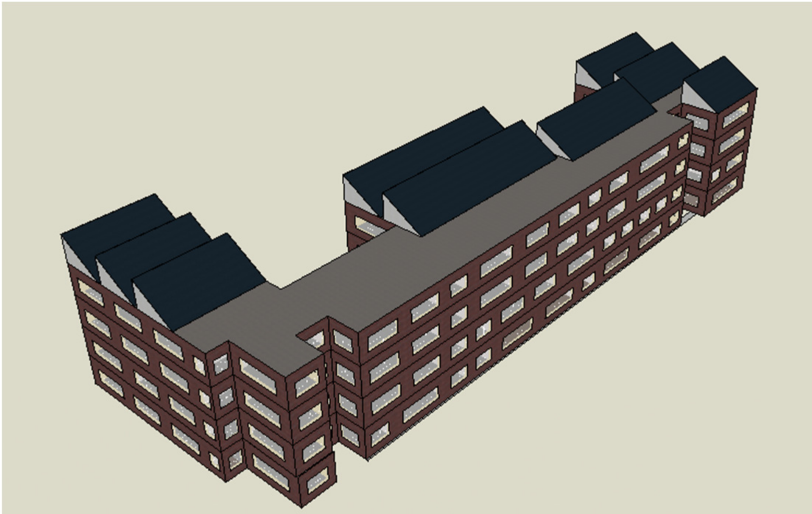


Figure 2. Campus office building used in the case study.

Indoor and outdoor load factors and cooling and heating facilities were modeled similarly to actual buildings; Table 3 shows the design variables for external building elements and components.

Table 3. Building component design value.

External Wall	Internal Partitions	External Floor	Ground Floor	Roof	Air Exchange Rate
0.35 W/m^2·K	1.639 W/m^2·K	0.25 W/m^2·K	0.25 W/m^2·K	0.25 W/m^2·K	0.7 ac/h
Lighting					
Target illuminance	**Normalized power density**	**Luminaire type**	**Radiant fraction**	**Visible fraction**	**Lighting power density**
125 lux	125 lux	suspended	0.42	0.18	6.25 W/m^2

The primary energy source for both cooling and heating utilizes electricity. An energy heat pump operates the cooling, and the setpoint temperature was limited to 26 °C. An electric boiler and radiator operated the heating, and the setpoint temperature was limited to 20 °C. In the proposed optimization model, the ST and GSHP systems can replace the heating system, and the PV system can generate the electricity required for cooling and overall operation. Table 4 shows the heating, ventilation, and air-conditioning (HVAC) operating schedule.

Table 4. HVAC system timetable.

		Cooling	Heating
Setpoint temperature		26 °C	20 °C
Building operating period	Monthly	1 June–30 September	1 January–30 April, 31 October–31 December
	Hourly	08:00–20:00	

The energy consumption of the target building with the design variables applied was 206,985 kWh per year, and Figure 3 shows the monthly demand load.

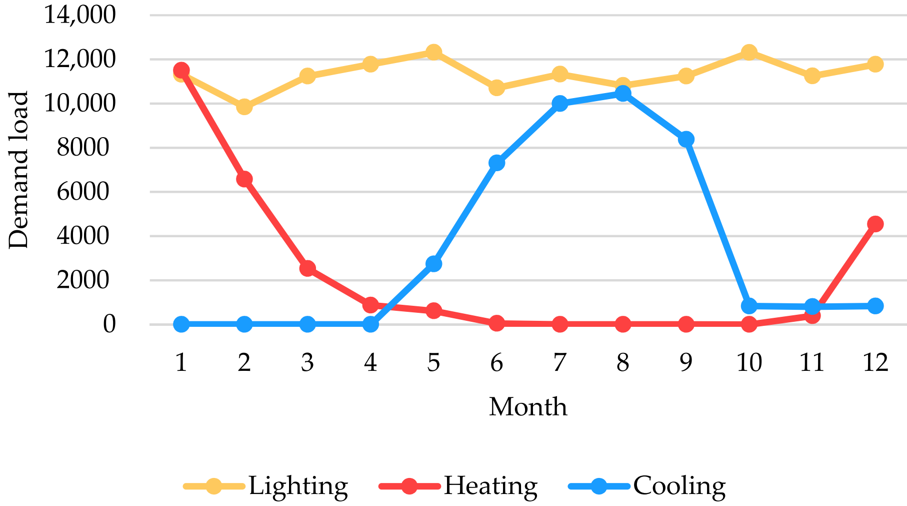


Figure 3. Monthly demand load.

According to the relevant laws, the renewable energy system used in the case study was modeled not to exceed 70% of the roof area. Furthermore, according to the Renewable 2020 Global Report [38], the PV system is the world's most widely installed system among renewable energy systems that can be installed in buildings. Therefore, the PV system's capacity is fixed, and the GSHP and ST systems satisfy the objective energy-saving amount and find the optimal point to maximize the LCC in the case study. A total of 77,463 energy simulation sets were used for each scenario, considering the 20, 40, and 60 kW of PV, ST, and GSHP capacities as test sets at 1 kW intervals.

The renewable energy systems were modeled within DesignBuilder using the simulation engine, Energy Plus [39].

A PV panel of about 10 m^2 was installed per 1 kW of PV capacity, and the inverter efficiency was 95%. The installation angle of PV and ST was the same at 45°. The usable electrical power produced by a PV system was calculated as follows:

$$G_{PV} = A_s \times G_T \times f_a \times \eta_{invert} \times \eta_{cell} \tag{11}$$

where G_{PV} represents the power generated by PV, A_s is the net area of the PV panel surface, G_T is the total solar radiation incident on PV array, f_a is the fraction of surface area with active solar cells, η_{invert} is the direct current to alternating current conversion efficiency, and η_{cell} is the module conversion efficiency.

The solar heat collectors of the ST system were targeted to evacuate tube collectors, and the thermal energy generated by the collectors was calculated as follows:

$$G_{ST} = F_R[I_s(\tau\alpha) - U_L(T_{in} - T_{air})] \tag{12}$$

where G_{ST} is the power generated by ST; F_R is an empirically determined correction factor; I_s is the total solar radiation on solar heat collectors; $\tau\alpha$ is the product of all transmittance and absorptance terms; U_L is the overall heat loss coefficient combining radiation, convection, and conduction terms; T_{in} is the inlet temperature of the working fluid; and T_{air} is the outdoor air temperature.

The GSHP system was considered an equation-fit-based model approach and was modeled using a vertical geothermal heat exchanger. In addition, the coefficient of performance was set to 3.5.

$$G_{GSHP} = C_1 + C_2\frac{V_{Load}}{V_{L,\,ref}} + C_3\frac{V_{source}}{V_{S,\,ref}} + C_4\frac{T_{Load}}{T_{ref}} + C_5\frac{T_{sorce}}{T_{ref}} \tag{13}$$

Here, G_{GSHP} is the power generated by GSHP, C_{1-5} represents the equation fit coefficients, V_{Load} is the volumetric flow rate of the load side, V_{Source} is the volumetric flow rate of the source side, $V_{L,ref}$ is the volumetric flow rate of the reference load side, $V_{S,\ ref}$ is the volumetric flow rate of the reference source side, T_{Load} is the load side entering water temperature, T_{Source} is the source side entering water temperature, and T_{ref} is the reference temperature (fixed at 283.15 K).

The rest of the settings were used as the default settings of DesignBuilder (V6.1.3) [37].

The initial IC and O&M were calculated on the basis of the Ministry of Trade, Industry, and Energy [40]. The system's lifetime is 7 years for PV, 10 years for ST, and 50 years for GSHP [41,42]. The system's maximum LCC period and life were assumed to be the same for GSHP to avoid incurring replacement costs. Table 5 shows the variables for the renewable energy system for retrofitting buildings.

Table 5. Cost information of renewable energy systems.

	Type	Price
Initial investment cost	PV	1610.38 $/kW
	GSHP	1476 $/kW
	ST	716 $/kW
Operation & maintenance cost	3% of initial investment cost	
Replacement cost	PV	161 $/kW every 7 years
	GSHP	0
	ST	71.6 $/kW every 10 years

To calculate the LCC based on the NPV, the real discount rate *i* must be calculated beforehand. The nominal discount and inflation rates were calculated using Equation (6) obtained from the economic statistics system of the Bank of Korea from 2013 to 2019. Consequently, *i* was determined to be 0.88%. Lee et al. [43] stated that when the discount rate is less than 3%, interest rate uncertainty does not significantly affect the experimental results. Therefore, interest rate uncertainty was not considered.

In Scenario 1, i.e., in the method of applying power generation directly to buildings, the unit cost of purchasing electricity was calculated using the Korean electric power corporation's electricity tariff system of 2021. The average electricity price was 0.072 $/kWh, high-voltage A and option II for educational service B. Table 6 summarizes the electricity price data [44].

Table 6. Electricity price for educational services [44].

Demand Charge ($/kW)	Price of Electricity ($/kWh)			
	Time Period	**Summer (June–August)**	**Spring/Fall (March–May, September–October)**	**Winter (November–February)**
6.34	Off-peak load	0.041	0.041	0.045
	Mid load	0.082	0.054	0.08
	Peak load	0.14	0.073	0.12

4. Results and Discussion

An optimization-based approach was used for decision-making about the retrofit plan of a campus building, which is an energy-intensive building. PV capacity is designated according to the objective energy-saving amount. When the objective energy saving was 10–20% of the expected energy consumption, PV was installed with 20 kW; when it was 20–30%, PV was installed with 40 kW; and when it was over 30%, PV was fixedly installed with 60 kW. The optimization model in this study can find the most effective renewable energy installation combination while considering energy savings and LCC for various available alternatives. In addition, decision-makers who find it challenging to perform simulation modeling or actual data analysis can use this model as a guideline for installing renewable energy systems according to the energy sales method.

Best solution results are shown through the Pareto-front, among the methods for solving multi-objective optimization. In a multi-objective problem, the best solution for one objective might be the worst for the other. For example, when the ratio of energy-saving is higher, the LCC value could decrease. Increasing the initial cost of installing the renewable energy system result from the increased capacity of the facility equipment, and energy systems can increase the energy-saving ratio.

The Pareto-front is the most efficient solution that can be achieved as a set of non-dominant solutions for two objective functions. Moreover, one objective function cannot be considered better than the other; hence, many solutions are optimally proposed. Thus, various optimized solutions are provided to help decision-making. The Pareto-fronts of the multi-objectives with the three scenarios are presented in Figure 4.

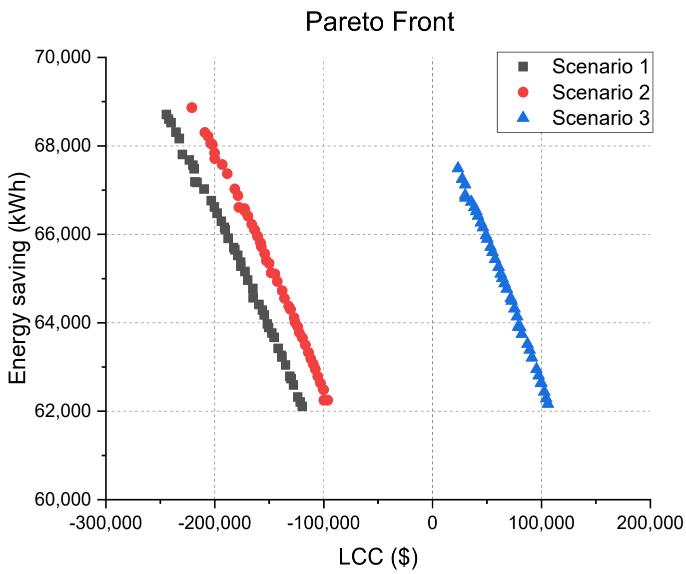
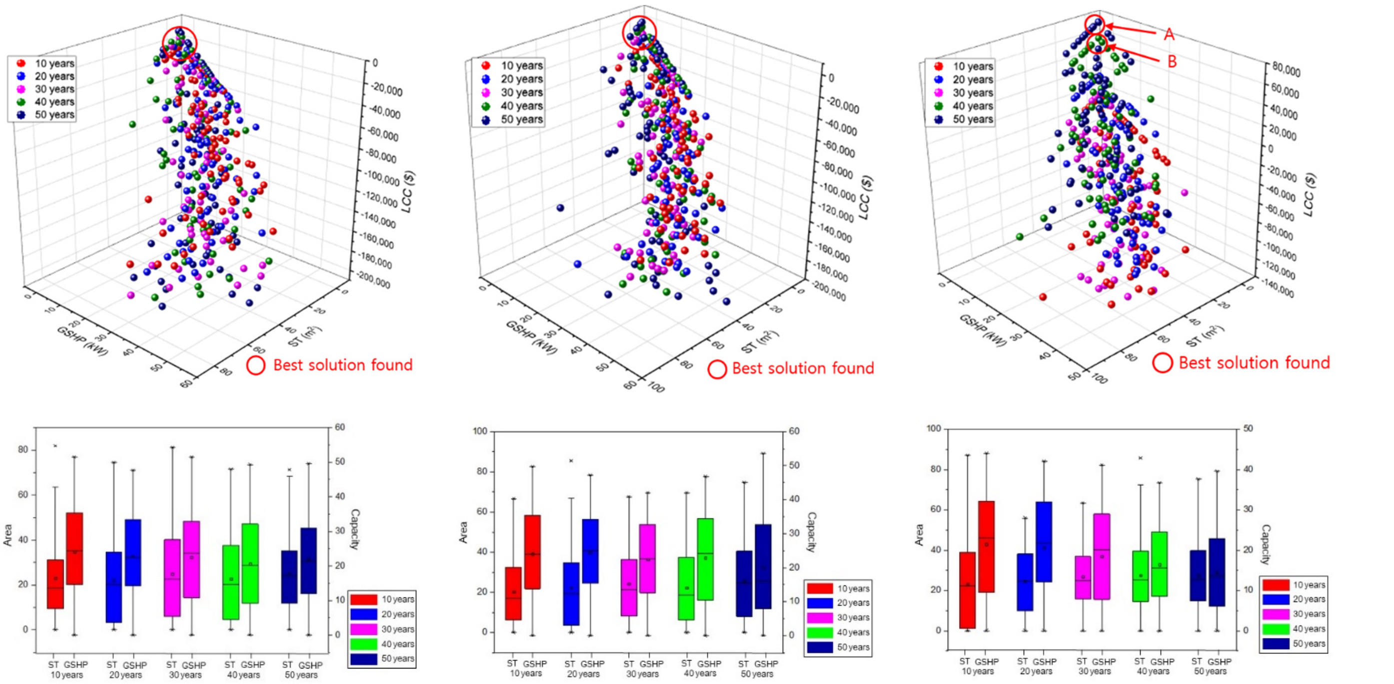


Figure 4. Pareto fronts by scenario.

The experimental results according to the scenarios are shown as a scatter plot showing the distribution of the entire optimal point and a box plot summarizing and visualizing the distribution of the scatter plot. The range of the box is 25–75% of the optimal point, and a line shows the median value. Moreover, the minimum and maximum values are indicated, and points show the outliers.

Figure 5 shows the optimization results according to the scenarios at the objective energy saving of 10–20%. The MOPSO optimization results according to each energy sales strategy scenario are discussed below. First, Figure 5a appears dense in the best solution zone from 10 to 50 years of lifetime. Additionally, the investment cost cannot be recovered in the entire lifetime. Therefore, it is proposed to install only PV systems according to the building's lifetime. Figure 5b also shows all years except for 10 years of a lifecycle in the best solution zone. However, only PV systems should be installed in buildings with a lifetime of 50 years because the investment cost could be recovered in the case. Figure 5c should recover the investment costs for 20 years in the scatter plot. When comparing points A and B with the highest LCC, point A proposes to install 28 m^2 ST in a building with a lifetime of 50 years and recovers a greater profit. However, point B shortens the period to 10 years and proposes a quick return on investment cost by installing a 15 m^2 ST on a building with a lifetime of 40 years. Table 7 shows the optimal points by year for each scenario.



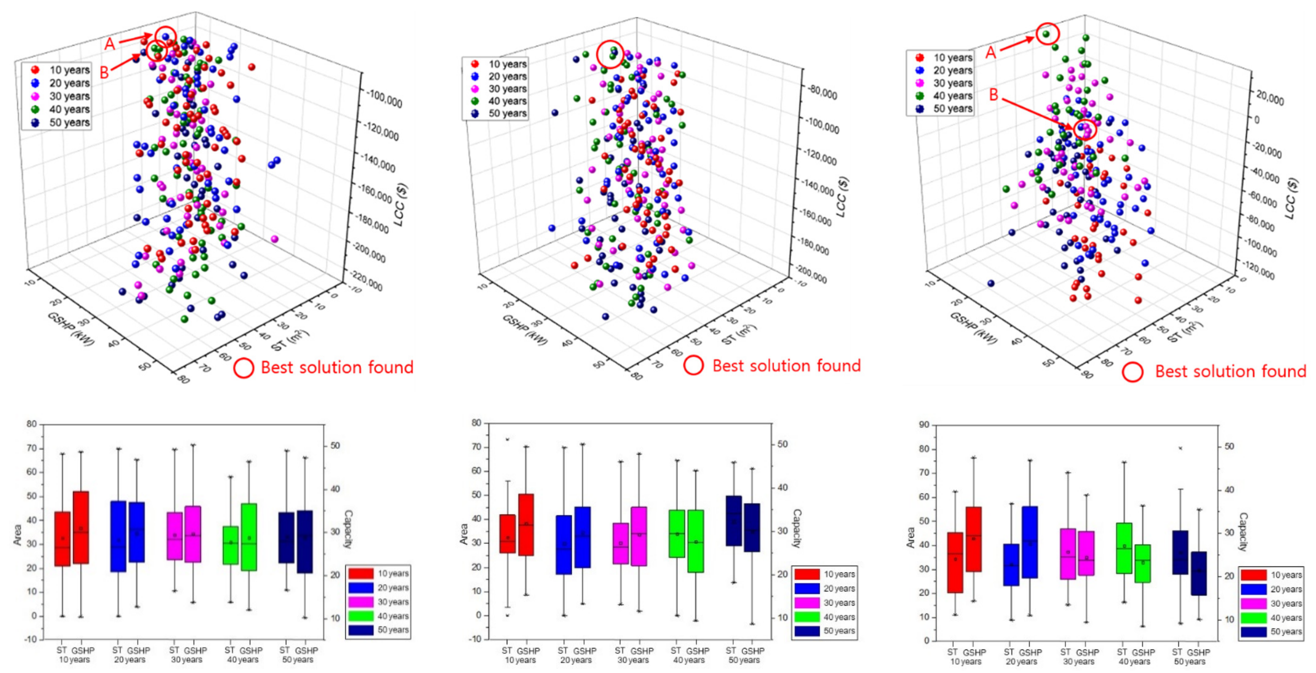
(a) (b) (c)

Figure 5. Objective 10–20% energy savings by scenario: (**a**) optimization results for Scenario 1; (**b**) optimization results for Scenario 2; and (**c**) optimization results for Scenario 3.

Table 7. Best solution found for 10–20% energy savings.

Years	Scenario 1			Scenario 2			Scenario 3		
	ST (m^2)	GSHP (kW)	LCC ($)	ST (m^2)	GSHP (kW)	LCC ($)	ST (m^2)	GSHP (kW)	LCC ($)
10 years	0	0	−24,150	0	0	−21,900	0	0	−4190
20 years	0	0	−18,820	0	0	−14,520	5	5	120
30 years	0	0	−15,140	0	0	−8960	8	0	5070
40 years	0	0	−10,660	0	0	−2760	15	5	33,020
50 years	0	0	−7560	0	0	1920	28	3	40,400

Figure 6 shows the optimization results according to the scenarios at the objective energy savings of 20–30%. In Figure 6a, the LCC was the highest at 20 years from point A. However, point B recorded a lower LCC even though the period was extended to 30 years. Therefore, it is advisable to choose Scenario 1 if the lifetime of the building is 20 years. Figure 6b shows the best value at a lifetime of 40 years, and then shows a lower LCC. In Figure 6c, point A was the optimum when the lifetime was 40 years, and B was the point at a lifetime of 50 years. The investment amount can be recovered at point A, but not at point B. Therefore, the ST system should be installed in a building with a lifetime of 40 years. Table 8 shows the optimal points by year for each scenario.



(**a**) (**b**) (**c**)

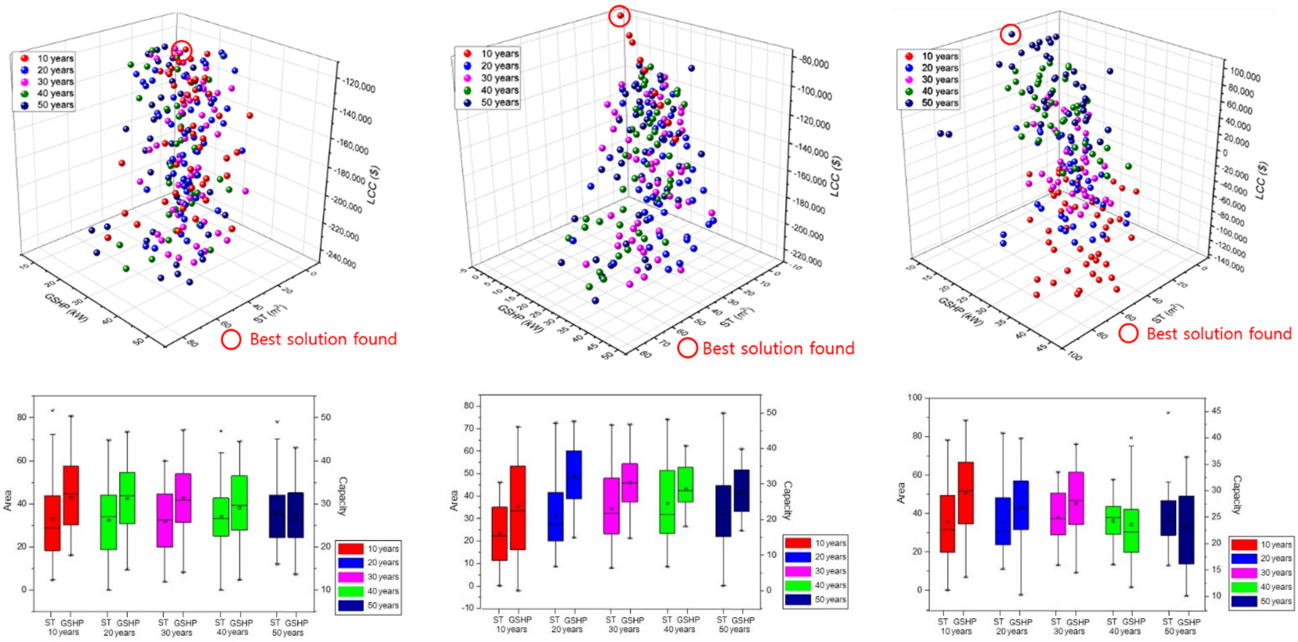
Figure 6. Objective 20–30% energy savings by scenario: (**a**) optimization results for Scenario 1; (**b**) optimization results for Scenario 2; (**c**) optimization results for Scenario 3.

Table 8. Best solution found for 20–30% energy savings.

Years	Scenario 1			Scenario 2			Scenario 3		
	ST (m^2)	GSHP (kW)	LCC ($)	ST (m^2)	GSHP (kW)	LCC ($)	ST (m^2)	GSHP (kW)	LCC ($)
10 years	26	10	−93,339	3	20	−86,490	15	14	−54,720
20 years	19	13	−91,090	12	16	−82,330	21	11	−20,470
30 years	11	17	−94,370	12	15	−80,100	21	13	7750
40 years	12	15	−93,000	16	13	−77,350	28	9	34,560
50 years	0	0	−94,320	0	0	−78,650	7	18	−42,090

Figure 7 shows the optimization results according to the scenarios at the objective energy saving of more than 30%. Figure 7a shows a high value at $−120,920 in 30 years, and the LCC decreased after that. We propose to perform a retrofit with a 30-year plan. In Figure 7b, the LCC increased continuously from 20 to 50 years; however, the initial investment cost cannot be recovered for the entire lifecycle period. Furthermore, when the lifecycle was 10 years, it was good to satisfy the energy savings only with PV. Figure 7c shows that the investment cost can be recovered from 30 years and that the LCC will increase. Therefore, it is advisable to plan the building's lifetime for as long as possible. Table 9 shows the optimum points when the objective energy savings are greater than 30%.

This study confirmed that the effect of installing renewable energy systems in campus buildings can vary, depending on the electricity price and energy sales policy. Furthermore, the proposed model assists in determining the optimal installation of renewable energy systems in campus buildings considering energy policies, such as the selection and ratio of renewable energy systems through retrofitting the building. In addition, useful results can be derived in improving the energy efficiency of existing buildings.



(**a**) (**b**) (**c**)

Figure 7. Objective energy-saving amount of greater than 30% by scenario: (**a**) optimization results for Scenario 1; (**b**) optimization results for Scenario 2; (**c**) optimization results for Scenario 3.

Table 9. Best solution found for ~30% energy savings.

Years	Scenario 1			Scenario 2			Scenario 3		
	ST (m^2)	GSHP (kW)	LCC ($)	ST (m^2)	GSHP (kW)	LCC ($)	ST (m^2)	GSHP (kW)	LCC ($)
10 years	11	19	−121,240	0	0	−75,270	9	20	−68,910
20 years	18	18	−125,300	18	16	−109,400	30	10	−17,300
30 years	14	17	−120,920	8	21	−105,890	20	15	26,180
40 years	23	14	−121,470	12	18	−98,150	19	15	69,820
50 years	18	15	−219,590	16	17	−96,280	32	10	105,880

5. Conclusions

The reckless use of fossil fuels causes concerns about carbon emissions and energy consumption. Specifically, the building sector needs energy saving, as it is an energy-intensive sector. In addition, energy policies such as regulations are being strengthened on energy savings when retrofitting existing buildings. Therefore, we considered economic factors and energy savings, including electricity price and energy sale strategies for campus buildings, and we presented installation guidelines for renewable energy systems' optimal combination and capacity. In this study, we considered the energy sales strategy according to energy policies, economic factors including electricity price, and energy savings, and we aimed to support decision-making to help install renewable energy systems' optimal combination and capacity.

The experimental results can be concluded and summarized as follows. Power generation consumption in buildings (Scenario 1) did not recover the initial investment cost in all cases. Therefore, it must choose the most energy-efficient point in Scenario 1. Even in Scenario 2, the initial investment cost cannot be recovered in most cases, but the energy efficiency was the best when the target energy saving was 50 years in the 10–20% range. In Scenario 3, the investment amount could be recovered in most sections. Therefore, we proposed to install PV 60 kW, ST 32 m^2, and GSHP 10 kW with a lifetime of 50 years that can recover the largest amount.

Herein, a simulation-based case study was conducted on an office building among campus buildings in Korea, and a base model was proposed to support decision-making for installing renewable energy systems. The case study confirmed that the effect of installation differs, depending on the electricity price and the energy sales method. Furthermore, the effect of applying renewable energy systems can vary according to the schedule and characteristics of the building, such as residential and research facilities on campus. Notably, the extended application of the proposed methodology in this study can be used as a decision-making model for the installation of renewable energy systems in the design stage of buildings and the retrofit stages of existing buildings in both Korea and other countries and regions.

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Nomenclature

LCC_T	Total amount used for the entire project period
$O\&M$	Operation and maintenance cost
LCC_{PV}	Sum of PV NPV
IC	Initial investment cost
LCC_{GSHP}	Sum of GSHP NPV
R	Replacement cost
LCC_{ST}	Sum of ST NPV
i	Real discount rate
EP	Electricity price
f	Inflation rate
$Benefit$	Monetary benefit from the energy generation
S_n	Energy unit price for each scenario
G_{PV}	Power generation of PV
G_{GSHP}	Power generation of GSHP
G_{ST}	Power generation of ST
OE	Objective energy saving
A_s	Net area of PV panel surfac
G_T	Total solar radiation incident on PV array
f_a	Fraction of surface area with active solar cells
η_{invert}	Direct current to alternating current conversion efficiency
η_{cell}	Module conversion efficiency
F_R	Empirically determined correction factor
I_s	Total solar radiation on solar heat collectors
$\tau\alpha$	Product of all transmittance and absorptance terms
U_L	Overall heat loss coefficient combining radiation, conversion and conduction terms
T_{in}	Inlet temperature of the working fluid
T_{air}	Outdoor air temperature
C_{1-5}	Equation fit coefficients

V_{Load}	Volumetric flow rate of the load side
V_{source}	Volumetric flow rate of the source side
$V_{L,\,ref}$	Volumetric flow rate of the reference load side
$V_{S,\,ref}$	Volumetric flow rate of the reference source side
T_{Load}	Load side entering water temperature
T_{sorce}	Source side entering water temperature
T_{ref}	Reference temperature

References

1. Waide, P.; Gerundino, D. International standards to develop and promote energy efficiency and renewable energy sources. *IEA Inf. Pap. Retrieved* **2007**, *6*, 2011.
2. Harish, V.S.K.V.; Kumar, A. A review on modeling and simulation of building energy systems. *Renew. Sustain. Energy Rev.* **2016**, *56*, 1272–1292. [CrossRef]
3. Chung, M.H.; Rhee, E.K. Potential opportunities for energy conservation in existing buildings on university campus: A field survey in Korea. *Energy Build.* **2014**, *78*, 176–182. [CrossRef]
4. Del Granado, P.C.; Wallace, S.W.; Pang, Z. The value of electricity storage in domestic homes: A smart grid perspective. *Energy Syst.* **2014**, *5*, 211–232. [CrossRef]
5. Zhang, K.; Li, J.; He, Z.; Yan, W. Microgrid energy dispatching for industrial zones with renewable generations and electric vehicles via stochastic optimization and learning. *Phys. A Stat. Mech. Appl.* **2018**, *501*, 356–369. [CrossRef]
6. Del Granado, P.C.; Pang, Z.; Wallace, S.W. Synergy of smart grids and hybrid distributed generation on the value of energy storage. *Appl. Energy* **2016**, *170*, 476–488. [CrossRef]
7. Iris, Ç.; Lam, J.S.L. A review of energy efficiency in ports: Operational strategies, technologies and energy management systems. *Renew. Sustain. Energy Rev.* **2019**, *112*, 170–182. [CrossRef]
8. Iris, Ç.; Lam, J.S.L. Optimal energy management and operations planning in seaports with smart grid while harnessing renewable energy under uncertainty. *Omega (UK)* **2021**, *103*, 102445. [CrossRef]
9. Kalogirou, S.A. Building integration of solar renewable energy systems towards zero or nearly zero energy buildings. *Int. J. Low-Carbon Technol.* **2015**, *10*, 379–385. [CrossRef]
10. Ahmadi, M.H.; Seyyedsadaghiani, M.; Ghazvini, M.; Shahriar, S.; Nazari, M.A. Ground source heat pump carbon emissions and ground-source heat pump systems for heating and cooling of buildings: A review. *Environ. Prog. Sustain. Energy* **2018**, *37*, 1241–1265. [CrossRef]
11. Beckers, B. *Solar Energy at Urban Scale*; John Wiley & Sons: Hoboken, NJ, USA, 2012.
12. Korea Power Exchange. *Electric Power Statistics Information System (EPSIS)*; Korea Power Exchange: Naju-si, Korea, 2017.
13. Kumbaroğlu, G.; Madlener, R. Evaluation of economically optimal retrofit investment options for energy savings in buildings. *Energy Build.* **2012**, *49*, 327–334. [CrossRef]
14. Hong, T.; Kim, J.; Lee, M. A multi-objective optimization model for determining the building design and occupant behaviors based on energy, economic, and environmental performance. *Energy* **2019**, *174*, 823–834. [CrossRef]
15. Fesanghary, M.; Asadi, S.; Geem, Z.W. Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm. *Build. Environ.* **2012**, *49*, 245–250. [CrossRef]
16. Diakaki, C.; Grigoroudis, E.; Kabelis, N.; Kolokotsa, D.; Kalaitzakis, K.; Stavrakakis, G. A multi-objective decision model for the improvement of energy efficiency in buildings. *Energy* **2010**, *35*, 5483–5496. [CrossRef]
17. Elbaset, A.A.; Barakat, S.; Ibrahim, H. Multi-objective optimization of grid-connected pv-wind hybrid system considering reliability, cost, and environmental aspects. *Sustain. Cities Soc.* **2020**, *60*, 102178.
18. Asadi, E.; da Silva, M.G.; Antunes, C.H.; Dias, L. A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB. *Build. Environ.* **2012**, *56*, 370–378. [CrossRef]
19. Wright, J.A.; Loosemore, H.A.; Farmani, R. Optimization of building thermal design and control by multi-criterion genetic algorithm. *Energy Build.* **2002**, *34*, 959–972. [CrossRef]
20. Malatji, E.M.; Zhang, J.; Xia, X. A multiple objective optimisation model for building energy efficiency investment decision. *Energy Build.* **2013**, *61*, 81–87. [CrossRef]
21. Mercado, K.D.; Jimenez, J.; Quintero, M.C.G. Hybrid renewable energy system based on intelligent optimization techniques. In Proceedings of the 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), Birmingham, UK, 20–23 November 2016; pp. 1–6.
22. González, A.; Riba, J.R.; Rius, A.; Puig, R. Optimal sizing of a hybrid grid-connected photovoltaic and wind power system. *Appl. Energy* **2015**, *154*, 752–762. [CrossRef]
23. Donald, R.; Nieto, A. A Compendium and comparison of 25 project evaluation techniques. Part 1: Net present value and rate of return methods. *Int. J. Prod. Econ.* **1995**, *42*, 79–96.
24. Koo, C.; Hong, T.; Kim, J.; Kim, H. An integrated multi-objective optimization model for establishing the low-carbon scenario 2020 to achieve the national carbon emissions reduction target for residential buildings. *Renew. Sustain. Energy Rev.* **2015**, *49*, 410–425. [CrossRef]

25. Bae, S.; Nam, Y.; da Cunha, I. Economic solution of the tri-generation system using photovoltaic-thermal and ground source heat pump for zero energy building (ZEB) realization. *Energies* **2019**, *12*, 3304. [CrossRef]
26. Suh, H.S.; Kim, D.D. Energy performance assessment towards nearly zero energy community buildings in South Korea. *Sustain. Cities Soc.* **2019**, *44*, 488–498. [CrossRef]
27. Korea energy Agency. *Renewable Energy Supply Status*; Korea Energy Agency: Ulsan, Korea, 2018.
28. Gul, M.; Kotak, Y.; Muneer, T. Review on recent trend of solar photovoltaic technology. *Energy Explor. Exploit.* **2016**, *34*, 485–526. [CrossRef]
29. Clerc, M. *Particle Swarm Optimization*; John Wiley & Sons: Hoboken, NJ, USA, 2010; pp. 1942–1948.
30. Moon, J.; Yoon, Y.; Kim, S.; Kim, K.; Kim, S.; Kim, J. Virtual optimal design of satellite adapter in parallel computing environment. *J. Korean Soc. Aeronaut. Space Sci.* **2007**, *35*, 973–982.
31. Lee, W.S.; Chen, Y.T.; Kao, Y. Optimal chiller loading by differential evolution algorithm for reducing energy consumption. *Energy Build.* **2011**, *43*, 599–604. [CrossRef]
32. Lee, J. LCC analysis model of building material that can be used in BIM environment. *Int. J. Civ. Eng. Technol.* **2019**, *10*, 259–269.
33. Kennedy, J. The particle swarm: Social adaptation of knowledge. In Proceedings of the 1997 IEEE International Conference on Evolutionary Computation (ICEC '97), Indianapolis, IN, USA, 13–16 April 1997; pp. 303–308.
34. Fadaee, M.; Radzi, M.A.M. Multi-objective optimization of a stand-alone hybrid renewable energy system by using evolutionary algorithms: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3364–3369. [CrossRef]
35. Coello, C.A.C.; Pulido, G.T.; Lechuga, M.S. Handling multiple objectives with particle swarm optimization. *IEEE Trans. Evol. Comput.* **2004**, *8*, 256–279. [CrossRef]
36. Yuan, X.; Zuo, J.; Huisingh, D. Green universities in China-What matters? *J. Clean. Prod.* **2013**, *61*, 36–45. [CrossRef]
37. DesignBuilder Software. Available online: https://designbuilder.co.uk (accessed on 10 September 2020).
38. Renewables REN21 Global Status Report. Available online: http://www.ren21.net (accessed on 8 November 2020).
39. EnergyPlus. *Energy Plus Engineering Reference*; DOE: Washington, DC, USA, 2019.
40. Ministry of Trade, Industry and Energy. *Press of Renewable Energy Supply Business*; Ministry of Trade, Industry and Energy: Sejong City, Korea, 2019.
41. Koh, J.; Park, Y.; Seo, D. Economic feasibility of various HVAC systems for commercial building and comparison of energy tariffs between Korea and USA. *Soc. Air-Cond. Refrig. Eng. Korea* **2008**, *20*, 599–607.
42. Huang, Y.X.; Liao, P.C.; Tsai, C.H.; Gui, S.Q. Modeling the relationships of factors affecting dissemination of ground source heat pump (GSHP) in China. *Adv. Mater. Res.* **2013**, *723*, 976–984. [CrossRef]
43. Lee, J.; Yang, H.; Lim, J.; Hong, T.; Kim, J.; Jeong, K. BIM-based preliminary estimation method considering the life cycle cost for decision-making in the early design phase. *J. Asian Archit. Build. Eng.* **2020**, *19*, 384–399. [CrossRef]
44. KEPCO. Electric Rates Tables. KEPCO, 2021. Available online: https://cyber.kepco.co.kr/ckepco/front/jsp/CY/E/E/CYEEHP00204.jsp?menuCd=FN0201060204 (accessed on 11 January 2021).